

Exploring CP phase in τ -lepton Yukawa coupling in Higgs decays at the LHC

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Abstract

We study the prospect of determining the CP violating phase in τ -lepton Yukawa coupling at the Large Hadron Collider (LHC). While present run is already exploring the production of a pair of the third generation τ leptons from Higgs decay, these measurements are not sensitive enough to constrain the CP violating phase. Several CP odd observables are proposed and analyzed utilizing the dominant channels with semi-invisible hadronic decay of τ . Several asymmetries corresponding to the T odd momentum correlations are also studied and their sensitivities to the CP violating phase in tau-lepton Yukawa couplings are estimated at 13 TeV LHC with 300 fb^{-1} of integrated luminosity. We find that the asymmetries can be as large as 40% for a pure pseudoscalar Higgs boson couplings.

Keywords: Higgs, Tau lepton, CP violating phase, Yukawa coupling, Hadron Collider

1. Introduction

The Large Hadron Collider (LHC) has achieved a milestone when it discovered a Standard Model (SM) like boson with mass around 125 GeV in its runs at 7 and 8 TeV [1, 2]. With the current data, the accuracy is still not adequate enough to confirm/refute it to be the SM Higgs. The data as of now allows for the significant deviations in Higgs couplings with the fermions and gauge bosons from the SM predictions. Thus there remains sufficient scope for new physics in the Higgs sector. In the current and future runs, precise determination of Higgs couplings with the SM fermions is one of the foremost goal for the LHC. In this context, owing to their large Yukawa couplings, the Higgs couplings with the third generation fermions *viz.* $Ht\bar{t}$ and $H\tau^+\tau^-$ become crucial. Moreover, heavier fermions from the third generation held the clue to the electroweak symmetry breaking (EWSB), and thus are expected to shed light upon different aspects such as, coupling structure and CP properties of the resonant state. In a particular scenario with beyond the SM (BSM), new physics effects contributing in these couplings can also be constrained further.

Another intriguing open question in particle physics is the CP violation (CPV) which still lacks a full understanding. CPV has been experimentally found and extensively studied in the mixings and decays of K and B systems. It also plays a crucial role in observed baryon asymmetry of the universe. In fact, it is one of the three Sakharov's conditions to explain the asymmetry. In the SM, the only source of CPV is the phase associated with the Cabibbo-Kobayashi-Maskawa (CKM) inter-generational quark mixing matrix. However, the amount of CPV present in the SM cannot adequately explain the baryon asymmetry. The Higgs sector of the SM is CP conserving as all the Higgs couplings are CP even. However, extensions of the SM like two-Higgs doublet models (2HDM) and minimal supersymmetric standard model (MSSM) contain two Higgs doublets which lead to additional bosons in the model. One of these bosons leads to CP odd couplings with the SM particles. In the CP violating scenarios of these models, all the three scalars mix with each other leading to the CP violating couplings with other particles in the model [3, 4].

Currently the studies of the spin and parity of the Higgs boson based on the combination of channels producing EW gauge bosons γ, W, Z point to a spin-0 particle with a purely pseudoscalar boson being ruled out at 95 % CL [5]. However possibility of a CP admixture with both the scalar and the pseudoscalar components is still allowed. Thus it would be one of the important goals of

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the next run of the LHC, which will be a high energy and high luminosity run, to determine the CP composition of the Higgs. A CP admixture Higgs would lead to the CP violating couplings with other SM particles. CPV in the Higgs sector is more prominent in its fermionic couplings than gauge boson couplings as the couplings of the pseudoscalar to gauge bosons are absent at tree level and can only arise at the one-loop level. Hence, the Yukawa couplings are known to be more democratic to CP even and CP odd bosons. Also, since Yukawa couplings are larger for third generation fermions and recognizing that it is difficult to study CPV in $Ht\bar{t}$ couplings at the LHC, in this letter we focus on the $H\tau^+\tau^-$ couplings when Higgs decays to resonant tau pairs once it is produced at the LHC.

In literature, several observables have been proposed to measure the CPV nature in the τ Yukawa couplings at the LHC [6–14]. Most of these observables rely on τ^\pm polarization and require the reconstruction of full τ^\pm spin four-vector in some rest frames. In the present study, we define our observables based on definite CP and T transformation properties. These observables are momentum correlations that are constructed from visible particle momenta in τ^\pm decays. In our study, we focus on the $\tau^\pm \rightarrow \pi^\pm \nu$ decay channel which is considered to be the best channel for parity determination and has the largest polarimetric power. One can safely accommodate other dominant hadronic channel $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$ using the same prescription however with reduced polarimetric power.

CMS (ATLAS) collaboration at CERN recently studied [15, 16] the tau pair production through Higgs decay, analyzed at center-of-mass energy 7 and 8 TeV run with corresponding integrated luminosity of 4.9 (4.5) and 19.7 (20.3) fb^{-1} respectively. To explore and detect these τ leptons, both hadronic and leptonic decay channels are considered, resulting into multiple different final state combinations from the pair. Both of these studies reported an excess of such events over the expected backgrounds, with a local significance 3.2 (4.5) standard deviation for the 125 GeV Higgs. The measured signal strengths in both cases are consistent with the SM expectation. However, one readily identifies the relatively smaller significance in the present scenario compared to the other decay modes of the Higgs owing to the challenging final states expected from the τ pair at the LHC. In presence of multiple invisible neutrinos at the final state, reconstruction of these events are rather complex.

We organize rest of the presentation as follows. In section 2, we introduce the importance of looking $H \rightarrow \tau^+\tau^-$ channel for the CP phase along with the corresponding Lagrangian parametrizing the CP transformation properties. Thereafter, in section 3 we introduce the CP observables and their construction which can be interesting. Since the rest frame observables are proved to be more effective, reconstruction of these semi-invisible events are primary necessary. We discuss some of the existing techniques and their efficiencies in reconstruction. All the results together with the capability of studying CP phase is finally pre-

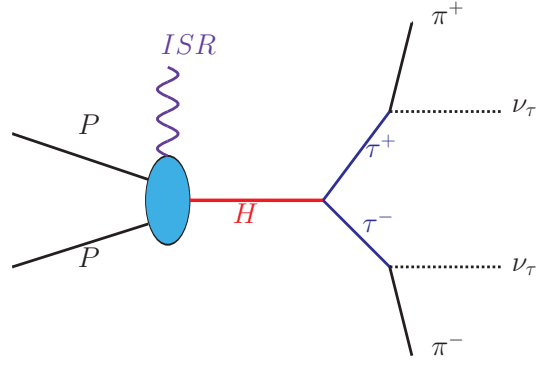


Figure 1: Representative diagram for $h \rightarrow \tau^-\tau^+$ with tau lepton decay hadronically via one prong decay channel. We assign momenta for the final state invisible (neutrinos) and visible (pions) particles as q_i and p_i respectively with $i = 1, 2$.

sented in section 3 before concluding in section 4.

2. Higgs boson production and decays

In this work, we study Higgs production via gluon fusion mechanism though our methodology to determine the CP phase in the $H\tau^+\tau^-$ coupling which can easily be applied to any other Higgs production processes, such as, VBF process or the associated vector boson productions. Following the Higgs production, we study the decay mode $H \rightarrow \tau^+\tau^-$. We consider both the τ^+ and τ^- to decay hadronically in order to minimize the loss of kinematic information due to multiple missing neutrinos. For the τ 's decay modes, we take into account the following 1-prong decays in our analysis: $\tau^\pm \rightarrow \pi^\pm \nu_\tau$. A representative diagram for the Higgs production and its decay to $\tau^+\tau^-$ followed by τ decays has been shown in Fig. 1.

In our analysis, we consider the Higgs boson to be a CP admixture and does not have a definite CP transformation properties. As mentioned earlier, the model for such a scenario could be any extension of a Higgs sector such as 2HDM, MSSM etc. with a CP violation in Higgs couplings. The Yukawa terms in the Lagrangian for such a Higgs boson can be parameterized as following:

$$\mathcal{L} \supset -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} H \bar{\tau} (\cos \alpha + i \gamma_5 \sin \alpha) \tau \quad (1)$$

where τ and H are the physical fields, respectively, y_τ is the effective strength of the τ -Yukawa interaction and α denotes the degree of mixing of the scalar and pseudoscalar component of the Higgs boson. For the SM Higgs boson, α vanishes identically at tree level reproducing a CP even Higgs and $y_\tau = m_\tau/v$. The CP phase can vary in the full range $(0, 2\pi)$ with $\alpha = \pi/2$ corresponds to a pure pseudoscalar and $\alpha = \pi/4$ to a maximally CP-violating case. Here to go forward we keep the y_τ fixed to the SM value and only vary the CP phase of the τ -Yukawa coupling to study the deviations in the expectation values of the observable with respect to the CP phase.

In our analysis, we consider Higgs mass $M_h = 125$ GeV. We have incorporated the anomalous Higgs couplings to tau leptons in **Madgraph** [17] using **FeynRules** [18]. The decays of the taus are handled with the tau-decay model implemented in **Madgraph**. We use **Madgraph** to generate the parton level events which are then passed to the **Pythia** [19] for our analysis.

3. Observables

The Higgs spin and parity information are coded into the correlations between τ^+ and τ^- spins. The spin of τ^\pm and correlation between τ^+ and τ^- spins are not directly measurable rather they are determined from the distribution of their decay products. They may also manifest themselves in the correlations among momenta of the τ^\pm decay products in particular to the plane transverse to $\tau^+\tau^-$ axes. This is because the decay distribution of $(H/A \rightarrow \tau^+\tau^-)$ is proportional to $d\Gamma \propto (1 + s_{||}^{\tau^+} s_{||}^{\tau^-} \pm s_{\perp}^{\tau^+} s_{\perp}^{\tau^-})$ [20] where $||$ and \perp denote the longitudinal and transverse components of τ^\pm spin with respect to Higgs momentum as seen from the $\tau^+\tau^-$ rest frame.

Taking into account of the aforementioned fact and recognizing that a triple product correlation is sensitive to a scalar and pseudoscalar contribution, we study several simple triple product correlations constructed out of momenta of the particles involved in the process. We utilize the momenta of the τ^+ , τ^- and their decay products, i.e., π^\pm , to construct momentum correlations. Under CP, $\vec{p}_{\tau^-} \xrightarrow{CP} -\vec{p}_{\tau^+}$ and $\vec{p}_{\pi^-} \xrightarrow{CP} -\vec{p}_{\pi^+}$. A triple product correlation transforms under CP as: $\vec{p}_{\tau^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \xrightarrow{CP} -\vec{p}_{\tau^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$. Thus, all the observables listed in Table 1 are CP odd and T odd¹. Note that the list does not exhaust all possible combination of triple product correlations involving particle momenta involved in the process. In principle, one could also include each neutrino momenta in constructing these correlations provided that they are determined at the LHC. Here we focus only on those combinations having substantial sensitivity.

The amplitude for the full Higgs decay chain $h \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$ can be written as

$$\begin{aligned} \mathcal{M} &\propto \bar{u}_{\nu_\tau}(\not{p}_{\tau^-} + m_\tau)(\cos\alpha + i\gamma_5 \sin\alpha) \\ &\times (-\not{p}_{\tau^+} + m_\tau)P_L v_{\bar{\nu}_\tau}. \end{aligned} \quad (2)$$

In a full matrix element squared, one would get CP angle α independent and dependent terms. Here we are only interested in α dependent terms. The decay distribution for this process contains a triple product correlation like the ones we have listed in Table 1 which one can get after summing over all the fermion spins in terms of $\epsilon_{\mu\nu\rho\sigma}p_{\tau^-}^\mu p_{\tau^+}^\nu p_{\pi^-}^\rho p_{\pi^+}^\sigma$. Here we have replaced neutrino momentum by $p_{\nu_\tau} = p_{\tau^-} - p_{\pi^-}$.

¹Henceforth, T will always refer to naive time reversal, i.e., reversal of all momenta and spins without interchanging the initial and final states.

Observables	Frame
$\mathcal{O}_1 = (\vec{p}_{\tau^-} - \vec{p}_{\tau^+}) \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$	ZMF
$\mathcal{O}_2 = (\vec{p}_{\tau^-} - \vec{p}_{\tau^+})^h \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})^\tau$	Prime
$\mathcal{O}_3 = (\vec{p}_{\pi^-} - \vec{p}_{\pi^+})^\tau \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})^h$	Prime
$\mathcal{O}_4 = (\vec{p}_{\pi^-} - \vec{p}_{\pi^+})^h \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})^\tau$	Prime

Table 1: T odd observables constructed in the process $h \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^-\nu\bar{\nu}$ at the LHC. All the observables have the definite CP and T transformation properties. Observables \mathcal{O}_1 have been defined in the Higgs rest frame or ZMF frame, while \mathcal{O}_{2-4} are defined in prime frame (defined in the text).

We consider two different frames to study these momentum correlations. Observable \mathcal{O}_1 has been defined in $\tau^+\tau^-$ zero momentum frame (ZMF) in which both τ^+ and τ^- are back-to-back (also known as ‘‘Higgs rest frame’’). In the ZMF frame, due to the large difference in the Higgs boson mass and the τ lepton mass, the τ^\pm are highly boosted leading to highly collimated decay products along the direction of τ^\pm momentum. This brings in some difficulty to reconstruct momenta of each particle in the event and hinders the prospects of performing angular analysis in such a frame. To get around these setbacks, we also define a peculiar frame where one part of the scalar product, constructed using tau momenta or tau decay product momenta, is in the ZMF frame while the second part is constructed in τ^\pm rest frames (denoted as ‘prime’ frame). Observables $\mathcal{O}_{2,3,4}$ are defined in this frame and the superscript h or τ in the expression is to mark the corresponding rest frame. Note that one of the observable \mathcal{O}_2 was first introduced in [6], where efficiency was studied along with effects of cuts and smearing. Our results are consistent with that study. In addition we also present the asymmetry against the CP phase.

In this study, we mainly focus on the angular correlation among the triple products listed in table 1, i.e., $\cos\theta_i = \hat{P} \cdot \hat{Q}$ where P and Q are first and second terms of the scalar-triple products. We display the distributions of the observables $\cos\theta_{1,2,3,4}$ in Fig. 2 for a pure scalar and pseudoscalar Higgs boson. As expected we find that the distribution is symmetric for $\alpha = 0$ leading to the vanishing expectation values of these observables for a CP even Higgs. On the other hand, for a pure CP odd coupling i.e., $\alpha = \pi/2$, there is a significant distortion in the distributions relative to CP even case indicating that the observables are sensitive to CP violating phase α .

For observable \mathcal{O}_1 , one can notice that most of the events are located only at small range, around $\cos\theta_1 \sim [-0.1, 0.1]$. This is due to the fact that in the ZMF frame, τ^\pm are highly boosted that leads to collimated decay products. For each distribution shown in the figures, we also define a corresponding asymmetry as follows

$$A_i = \frac{1}{\mathcal{N}_{\text{tot}}} [\mathcal{N}(\cos\theta_i < 0) - \mathcal{N}(\cos\theta_i > 0)] \quad (3)$$

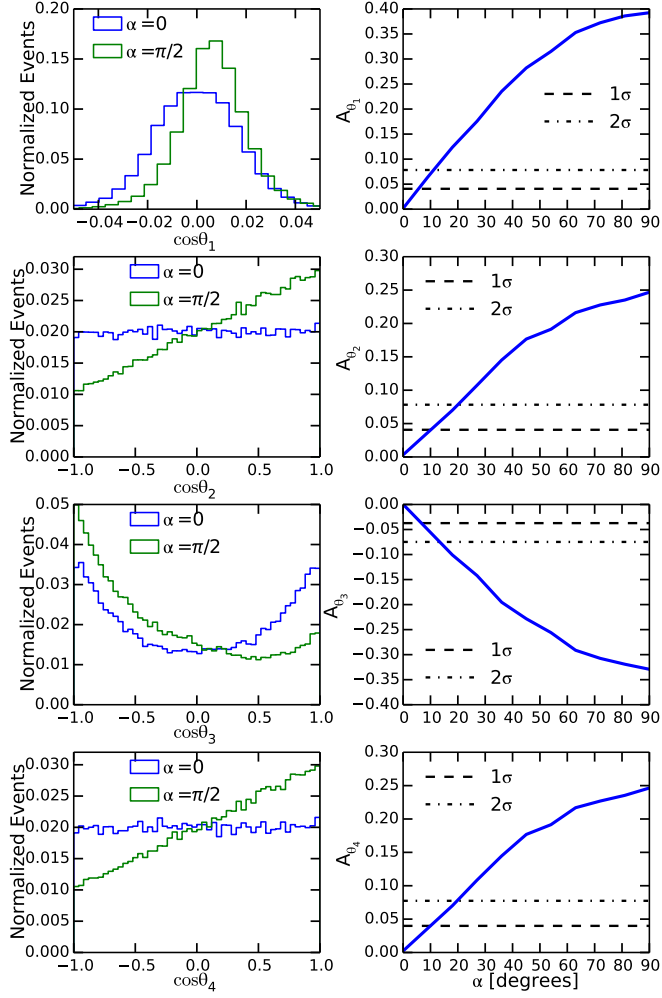


Figure 2: Distribution of $\cos \theta_i$ for observables O_1, \dots, O_4 considering two values of CP violating phase $\alpha = 0$ and $\pi/2$ for a pure scalar and pseudoscalar Higgs at the LHC. Variations of corresponding asymmetries against the phase α are also shown in the right plot. The dashed and dash-dotted line in right panel denote the 1σ and 2σ of statistical uncertainties (obtained using Eq. 4) in the measurement of asymmetries with 300 fb^{-1} of integrated luminosity at the LHC.

where \mathcal{N}_{tot} is the total number of events. We also study the behavior of these asymmetries as a function of CP phase α . These asymmetries have been displayed in the right panels of Fig.2 for observables O_1 and $O_{2,3,4}$ respectively.

From the plots of asymmetries, we notice that the asymmetry is vanishing for a CP even scalar ($\alpha = 0$) resulting from a symmetric $\cos \theta_i$ distribution. For a pure pseudoscalar ($\alpha = \pi/2$), the asymmetry is the largest for the observable O_3 with the value $\sim 33\%$ while observables $O_{2,4}$ also provide the modest asymmetry of $\sim 25\%$. Also, the slopes of the asymmetries are fairly steep indicating a good sensitivity to the measurement of CP phase α .

We now discuss the sensitivity of these asymmetries to the measurement of CP phase, α , in $H\tau^+\tau^-$ coupling at the 13 TeV LHC. For this, we take into account of the statistical uncertainty in the measurement of an asymmetry

which is defined as follows

$$\Delta\mathcal{A} = \frac{\sqrt{1 - \mathcal{A}_{\text{SM}}^2}}{\sqrt{\sigma_{\text{SM}} \mathcal{L} \epsilon}}, \quad (4)$$

in terms of integrated luminosity \mathcal{L} , expected value of an asymmetry² in SM \mathcal{A}_{SM} and total tau pair cross section in the SM σ_{SM} . Experimental efficiency factor ϵ arise to detect of such events after inclusion of realistic cuts and background elimination can be estimated and used for this calculation. We estimate this effect utilizing the recent analysis Higgs boson searches in its hadronic τ decays. Efficiency factor (ϵ in Eq. 4) by which the tau pair events from Higgs in gluon gluon fusion (ggF) is analyzed in the hadronic decay τ turns out to be nearly 8.9%. The ϵ is the ratio between the number of events after the realistic cuts and the expected number of events. For the realistic events, we took the number ATLAS got in ref. [16] for ggF channel. The expected number of events is obtained by the product of the theoretical Higgs production cross section via gluon fusion at 8 TeV (19.27 pb), the Higgs decay branching ratio into tau pairs, tau decay branching fractions to charged pion and the luminosity. We have assumed this efficiency factor to be same for 13 TeV and used in the estimation of sensitivity of our observables.

In the right panel of Fig. 2, we display the 1σ and 2σ statistical uncertainty in the measurement of respective asymmetries through dashed and dot-dashed lines, respectively. The projection from the intersection point of the asymmetry curves and the 1 and 2 σ lines on the x-axis can be taken as the 1 and 2 σ limits imposed by the corresponding asymmetries on the CP phase α at the 13 TeV LHC. In presenting these limits, we consider 300 fb^{-1} of integrated luminosity. From the figures, we find that the asymmetry A_{θ_1} is the most sensitive of all the asymmetries we analyzed in this analysis and the measurement of this asymmetry can determine the CP phase α up to 12 degrees at 2σ CL. The asymmetries A_{θ_2} , A_{θ_3} and A_{θ_4} can determine this angle up to 20, 15 and 20 degrees, respectively at 2σ CL for 13 TeV LHC.

Present formalism and efficiency of constructed CP observables are studied utilizing the truth information, from the full event momenta generated in simulation. However, to get any meaningful information on the usefulness of these CP observable's against the LHC events, it remains to see how precisely one can reconstruct these semi-invisible tau pair events from Higgs decay. Some of the recently proposed techniques in the literature constructed particularly for such scenario are in order. Popular and early proposal, such as, *collinear approximation* [21, 22] determine invisible neutrino momenta by assuming the tau decay products are collinear. With this assumption the neutrino(s) from tau take a fraction of tau momenta

²Although this definition is written in a general perspective when we tested several other variables, $\mathcal{A}_{\text{SM}} \sim 0$ for our present observables.

which results in reduction of unknowns to two and can be solved exactly using missing transverse momenta constraints. *Missing mass calculator* [23, 24] solves for the four unknown of the neutrinos momenta and remaining two unknowns are parametrized using a probability function. The probability function utilizes an independent measurement of angular separation between visible and invisible particles from $Z \rightarrow \tau\tau$ channel. *Displaced vertex method* [25] assume at least one tau decays via 3-prong channel. It determines the tau momenta by utilizing the secondary vertex information and available constraints in the event. *Constraint \hat{s} method* [26] assigns momenta to tau after optimizing the phase space by taking care of available kinematic constraints. *M_{2Cons} method* [27, 28] is a 3D M_2 variable which minimizes phase space by utilizing the Higgs mass and transverse momenta constraints and gives generic mass measurement prescription for antler decay topology. The reconstruction of neutrino momenta, in present scenario, proved to be very precise. Recently developed reconstruction [29] utilizes the tau mass-shell, missing transverse constraints together with measured impact parameter to reconstruct the semi-invisible events. The impact parameter is the perpendicular distance of pion momentum direction from the Higgs boson production vertex which can be identified using the tracks of jets produced with Higgs.

While there are many reconstruction methods, not all of them are sensitive to the CP observables defined above. Any method which approximate the neutrino momenta exactly along the tau direction may not be sensitive to these CP variables because each of them are vector triple product. The reconstruction of these variables is beyond the scope of this paper and will be done in forthcoming work.

4. Summary and Conclusion

The determination of the CP properties of Higgs boson is one of the important aims at the large hadron collider (LHC) in its current and future runs. The goal is facilitated in the Higgs couplings to the third generation of fermions, in particular τ^\pm leptons. Spin of τ^\pm and the correlations between them may provide a great insight to the CP properties of Higgs boson. However, these are not directly measurable and manifest themselves in the distribution of its decay products.

In spirit of the aforementioned fact that the spin correlations are reflected in final state distributions, we proposed several triple product correlations which are constructed from the momenta of various particles involved in the process. Recognizing that the sensitive observables are best represented at the rest frame, we consider two different type of frame to look into the correlations. These correlations have a definite CP and T transformation properties. We present the distribution of angular correlations obtained the various momentum correlations discussed earlier. These are shown to be sensitive to the CP phase in the $H\tau^+\tau^-$ couplings at the LHC.

We also constructed the asymmetries using each angular correlation and studied their behavior as a function of the CP phase. Some of these asymmetries are found to be as large as 35%. A statistical analysis of the sensitivity of these asymmetries on the measurement of CP phase is also undertaken taking into account the reconstruction efficiency of τ^\pm pair events at the LHC. It is found that with 300 fb^{-1} of integrated luminosity, the CP phase can be determined up to 15 degrees at the 13 TeV LHC.

Finally, we advocate a detailed detector level simulation with an actual reconstruction of τ^\pm momenta at the LHC in order to estimate the realistic efficiency of the variables proposed in the paper. While these practical questions are not addressed in this work, we feel that the interesting new features we found would make it worthwhile to address them in the future.

Acknowledgments

This work was funded by Physical Research Laboratory (PRL), Department of Space (DoS), India. P.S. acknowledges the support from the University of Adelaide and the Australian Research Council through the ARC Center of Excellence for Particle Physics (CoEPP) at the Terascale (grant no. CE110001004).

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